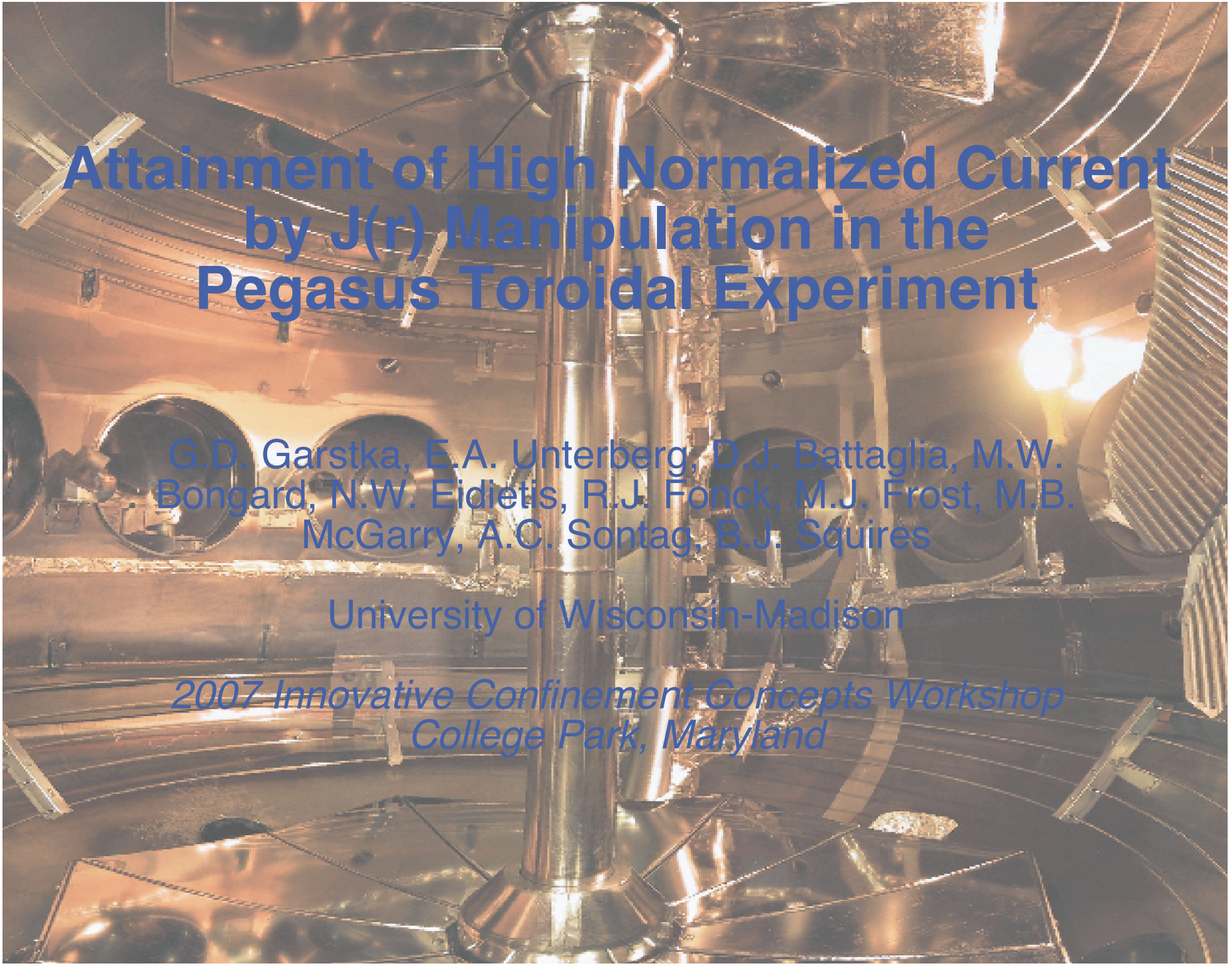


Attainment of High Normalized Current by J(r) Manipulation in the Pegasus Toroidal Experiment

G.D. Garstka, E.A. Unterberg, D.J. Battaglia, M.W. Bongard, N.W. Eidietis, R.J. Fonck, M.J. Frost, M.B. McGarry, A.C. Sontag, B.J. Squires

University of Wisconsin-Madison

2007 Innovative Confinement Concepts Workshop
College Park, Maryland

Abstract

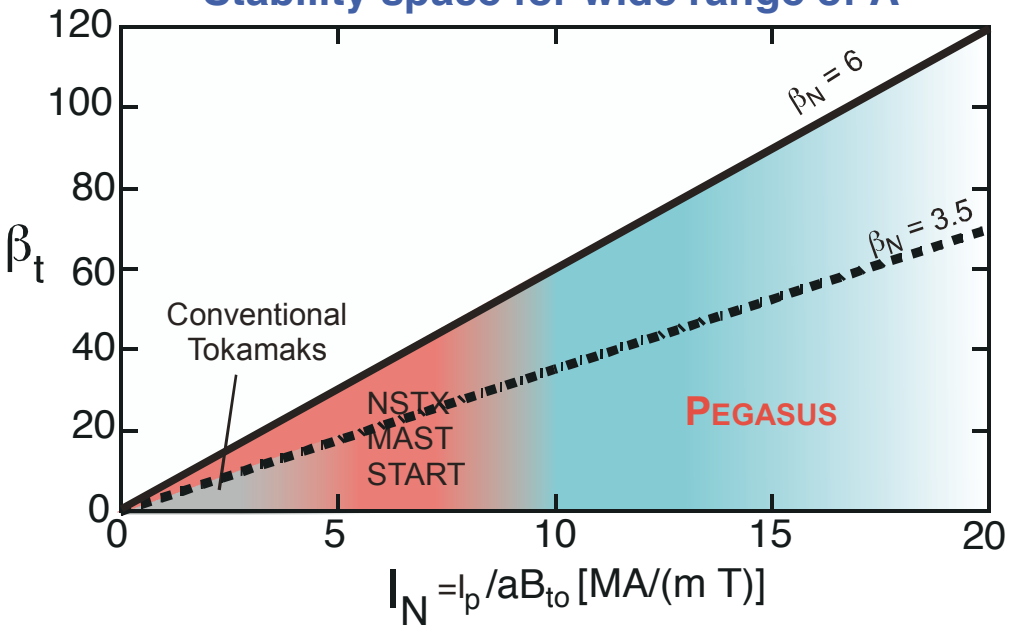
The operating space defined by the external kink mode boundary in a near-unity aspect ratio ST allows access to very high toroidal beta and I_N. Normalized current can be equivalently expressed as the toroidal field utilization factor I_p/I_{tf}, where I_{tf} is the current flowing in the centerpost. Values of $I_p/I_{tf} > 2$ ($I_N > 12$ MA/m-T) are expected to be stable to ideal MHD modes in the ultra-low-A Pegasus Toroidal Experiment. Simple inductively-driven plasmas on Pegasus had exhibited an operational limit of $I_p/I_{tf} \sim 1$, which was attributed to the early onset of large-scale low-order tearing modes in the plasma core. The use of point-helicity sources has greatly broadened the operating space of the device in the direction of low toroidal field. These sources can be employed as a preionization technique that facilitates ohmic startup and allows attainment of $I_p/I_{tf} \approx 1.5$ at low I_p (~ 50 kA). Using these sources for non-inductive startup via helicity injection provides access to $I_p/I_{tf} > 2$, again at low I_p and at very low field (0.01 T). In both cases, no large-scale tearing modes are evident. These observations, coupled with magnetic reconstructions indicating hollow J(R) with possible reverse shear, suggest that these sources provide significant modifications to the J(R) profile to allow stable discharge evolution. In addition, experiments conducted with strong toroidal field ramps indicate a positive plasma current drive and rapid increase in I_p/I_{tf} above unity until plasma confinement is degraded. Finally, exploitation of the new programmable ohmic current drive system provides more useful V-s and allows much finer control of Vloop than was previously available. This supports a broad startup operating space, enabling control of J(r) during the current ramp. Experimental studies are focusing on extending these techniques to higher I_p, and probing the external kink stability limits at A≈1.

Work supported by the United States Department of Energy Grant DE-FG02-96ER54375

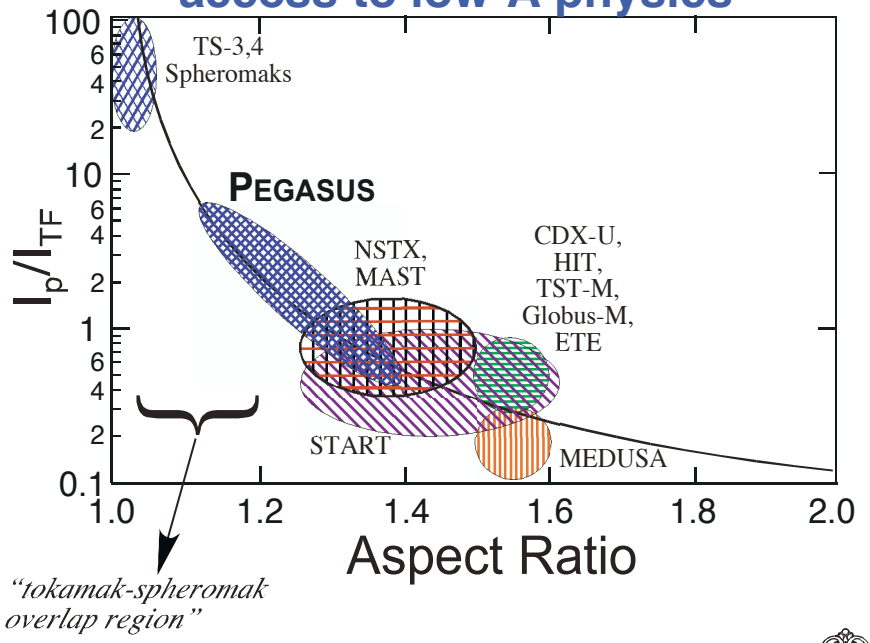
Pegasus Mission: Exploit unique properties of A→1 ST

- Stability and confinement at high I_p/I_{TF} and high I_p
  - Extension of tokamak studies
- Limits on β_t and I_p/I_{TF} (kink) as A→1
  - High kink-stable β_t achievable
  - Overlap between the tokamak and the spheromak
- Noninductive current drive and sustainment
  - Key for success of ST and tokamak in general

Stability space for wide range of A



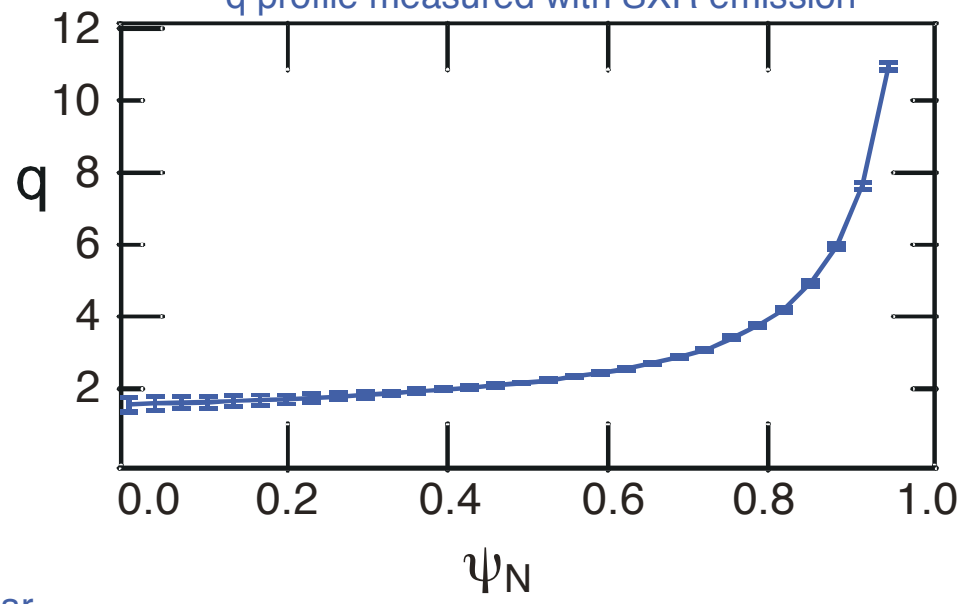
I_p/I_{tf} → figure of merit for access to low-A physics



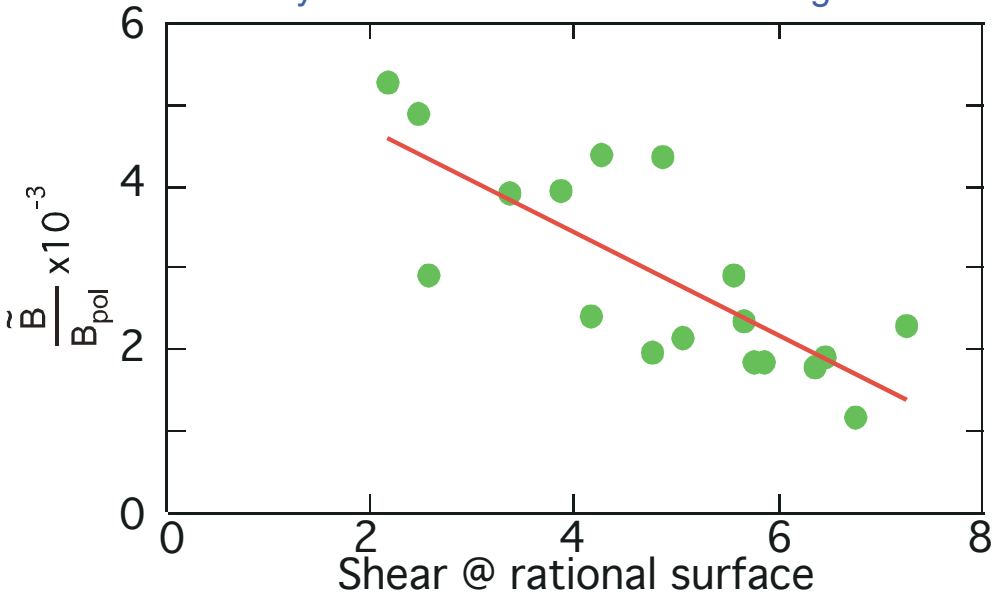
Phase I: Low-order tearing modes limit plasma current

- Maximum $I_p \approx I_{tf}$ limit
- Low-shear ST q-profile of ST ⇒ tearing mode instability
  - *large region of low magnetic shear near axis ⇒ large island widths*
  - *low TF operations ⇒ q<2 when highly resistivity*

q profile measured with SXR emission



TM activity decreased with increased magnetic shear

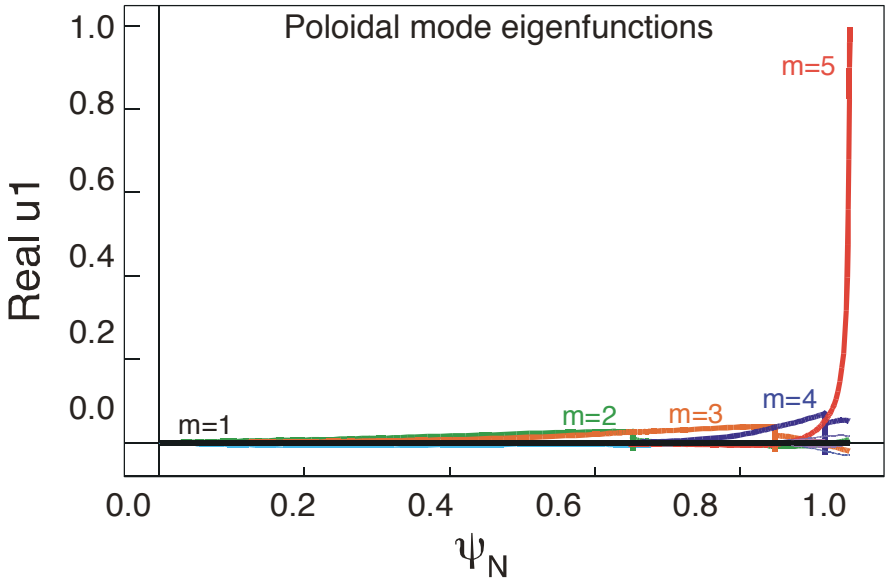


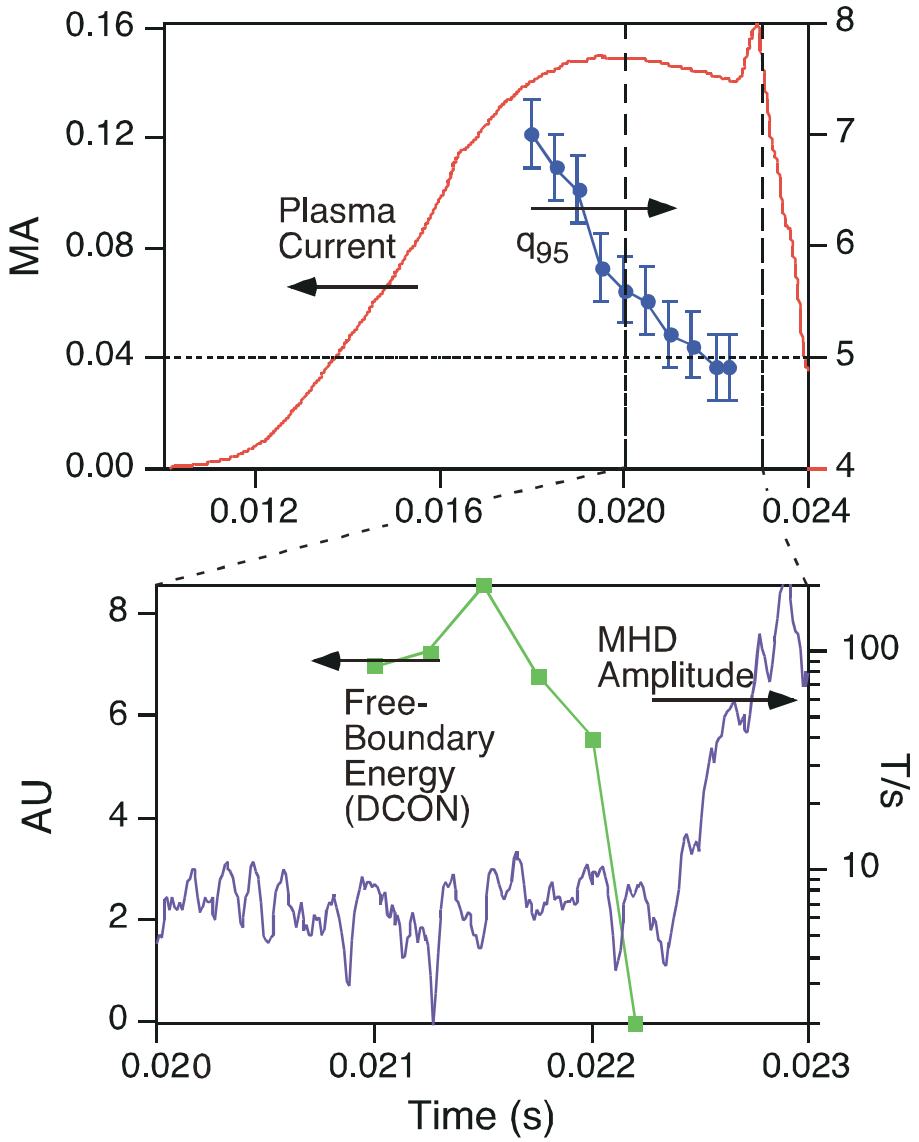
- Crude manipulation of q(r) reduced mode amplitude
  - *Increased shear, q_0 ⇒ delay tearing mode onset*

⇒ Access higher I_p/I_{TF} via higher q_0, T_e, shear

Phase-I: External kink observed at highest I_p

- Highest Phase-I I_p often disrupt
- q_{95} = 5 observed preceding disruption
  - ℓ_i=0.5 at this time
- DCON analysis ⇒ unstable to n=1 external kink
  - m=5 most unstable mode
- Consistent with theory expectation & high edge current





Expanded capabilities broaden access to high I_N

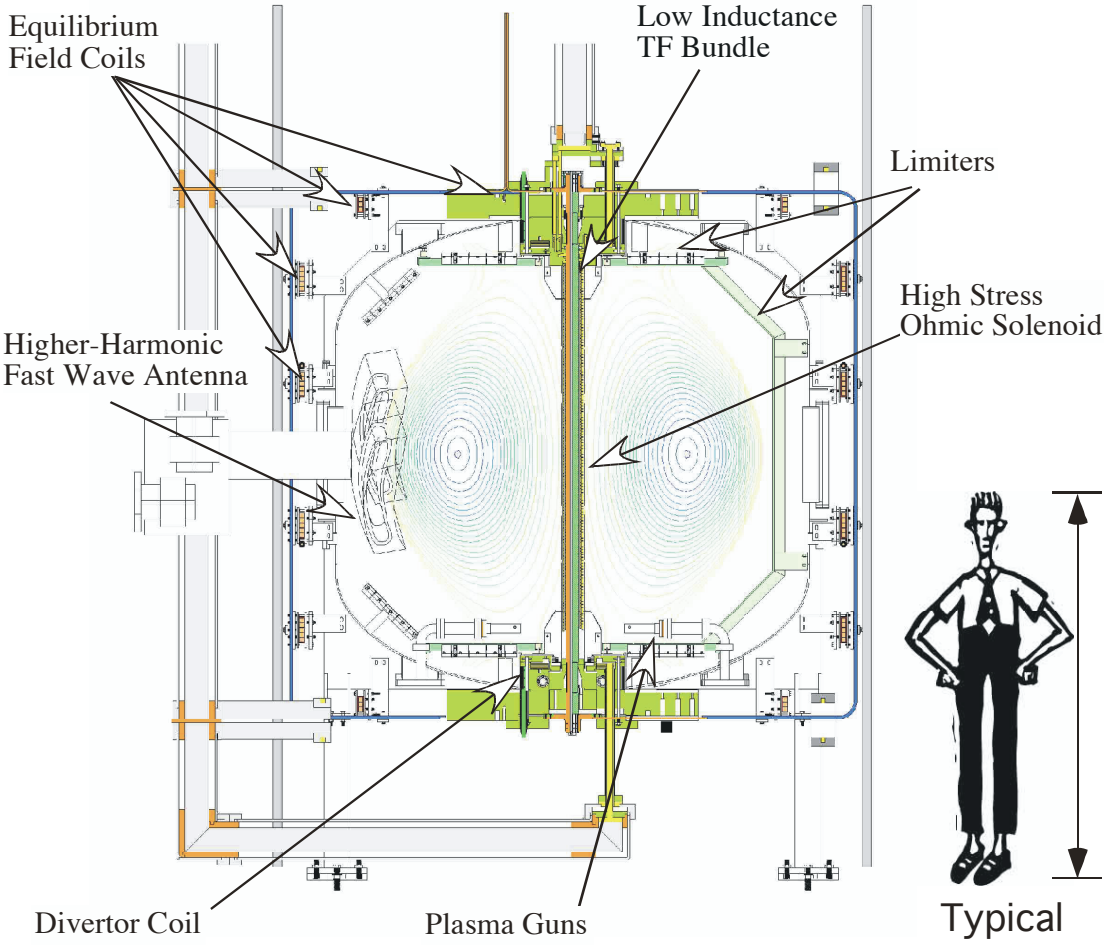
Phase I		Phase II
- Limited current profile control - *coils controlled with simple LRC resonant circuits*	⇒	- Manipulate current profile - *V_{loop} & position/shape control, $B_t(t)$, Electrostatic current sources*
- Low-order rationals appear early - *large low magnetic shear regions*	⇒	- Reduce η before low-order rationals appear - *V_{loop} & position/shape control, $B_t(t)$*
- TF: steady state compared to discharge - *high L_{tf} from 60 turn coil set*	⇒	- Transiently increase q during startup - *$B_t(t)$, V_{loop} control*

- **Facility modifications for expanded capability**
  - Power Supplies
    - *OH: effective V-s ↑ w/ increased waveform control*
  - Coil Sets
    - *Lower inductance TF set: 60 turns ⇒ 12 turns*
    - *PF Set: monolithic set ⇒ 8 independent sets*
    - *Divertor coil set installed*
  - Electrostatic Current Sources in Lower Divertor Region

Pegasus is a university scale, mid-sized ST

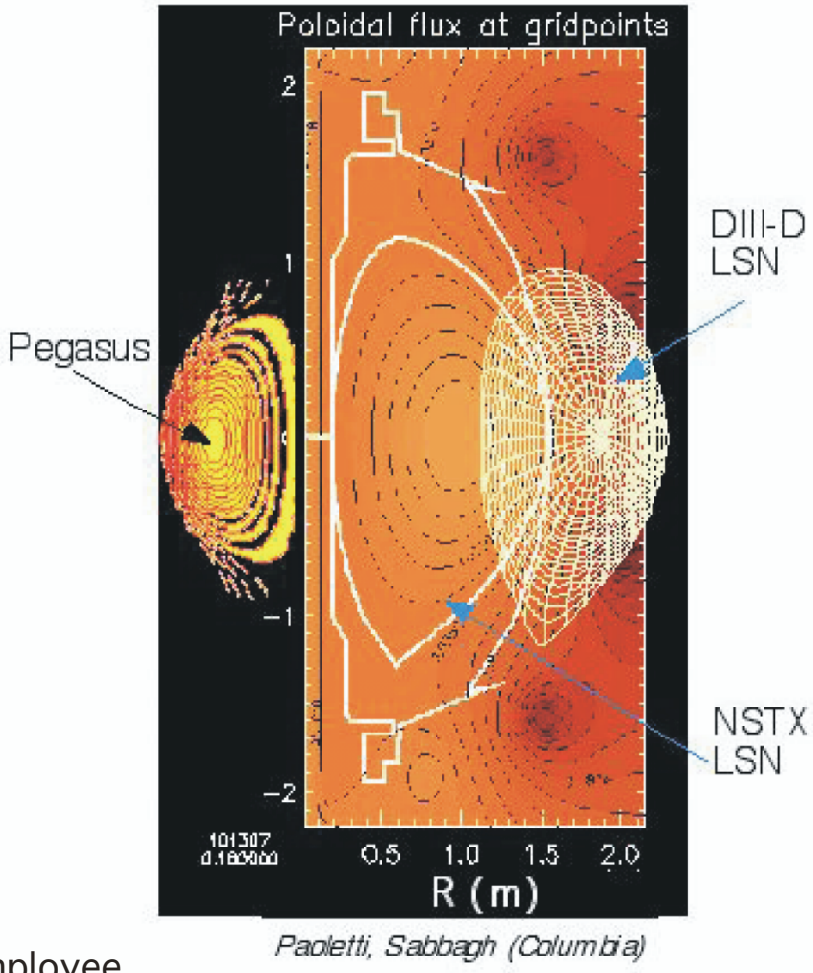
Experimental Parameters

Parameter	A	R (m)	I_p (MA)	I_p/I_{tf}	I_N (MA/m-T)	κ	τ_{shot} (s)	P_{HHFW}(MW)
Achieved	1.15-1.3	0.2-0.38	≤ 0.175	≤ 2.2	6-12	1.4–3.7	≤ 0.02	0.2
Proposed Goals	1.12-1.3	0.2-0.45	≤ 0.30	≤ 3	6-20	1.4–3.7	≤ 0.05	1.0



Typical PEGASUS Employee ≈ 1.8 m

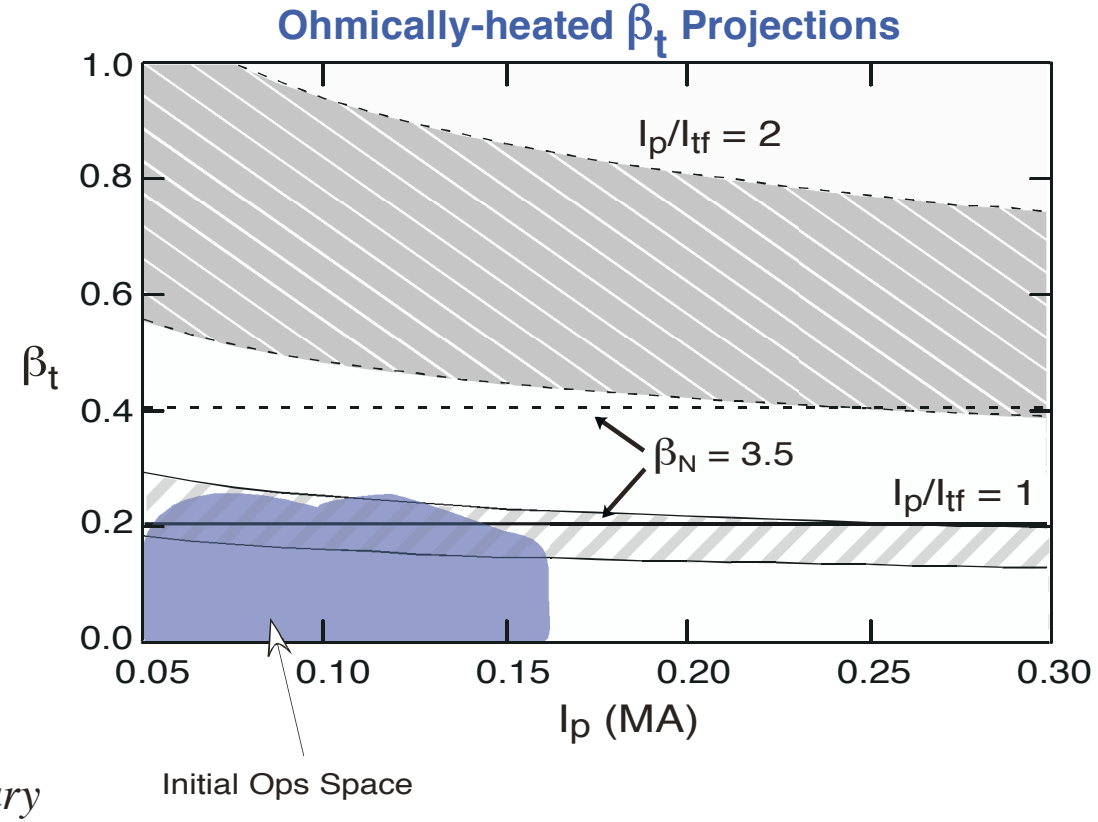
Equilibria comparison



Paoletti, Sabbagh (Columbia)

Modeling indicates access to high l_N

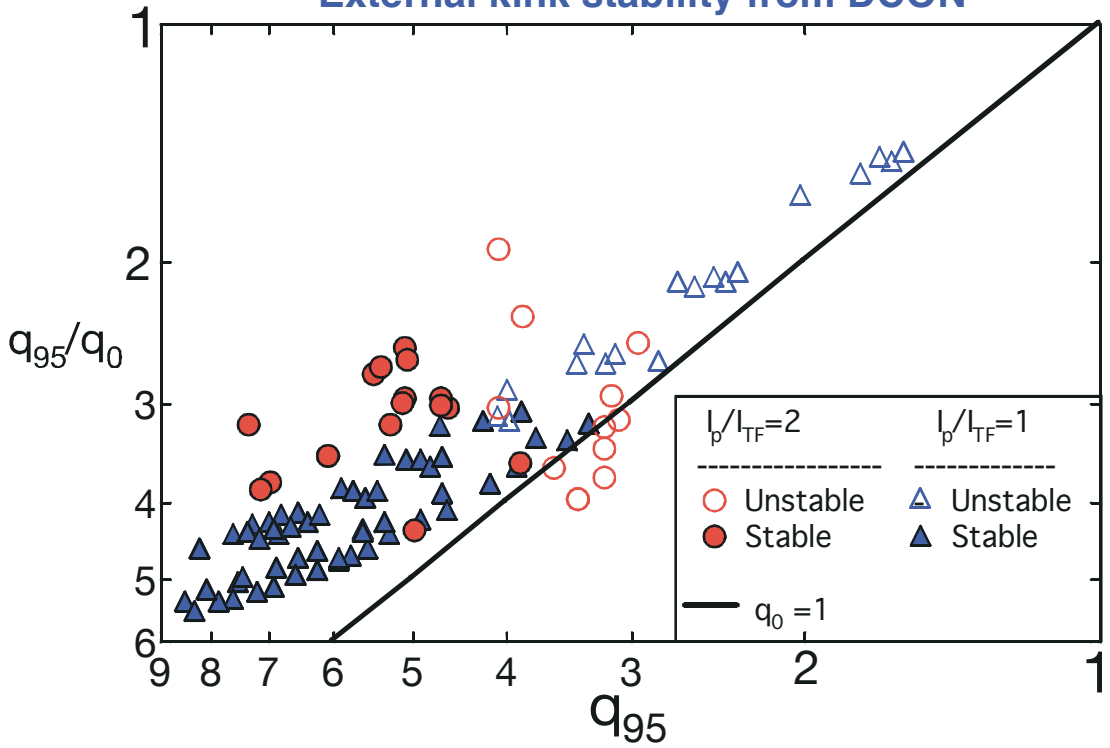
- **0-D confinement scaling calculations:**
  $l_p/l_{tf} = 2 \Rightarrow \beta_t = 40\text{-}70\%$
  - *Enables access to pressure stability boundaries*
  - *Consistent with initial data set*
- **TSC: Full ohmic flux (90 mV-s)**
  - *$I_p \sim 300$ kA attainable*
  - *Simulations corroborate:*
    - *$I_p/I_{tf} = 2$; $I_N \sim 12$ MA/m-T*
- **DCON stability modeling:**
  - *Found $I_p/I_{tf} = 2$ stable with $q_{95} > 4$*
    - *Consistent with known theory*
  - *Suggests $I_p/I_{tf} = 3$ kink stable boundary*
  - *Pressure profile affects under investigation*



Modeling of stability boundaries to guide experiment

- **Goal: To determine optimal parameters for external kink stability at high l_p/l_{tf}**
- **Base cases with l_p/l_{tf} = 2 and 3 used as starting points for further study**
  - *Variety of profiles and shapes studied to determine possible stability boundaries*
- **Studies ongoing to determine possible stability boundaries; key parameters for high l_p/l_{tf} operations**
  - *Initial indications show need for broad current profiles & high elongation for stability*

External kink stability from DCON



3 Unique Paths to high $I_p > I_{tf}$

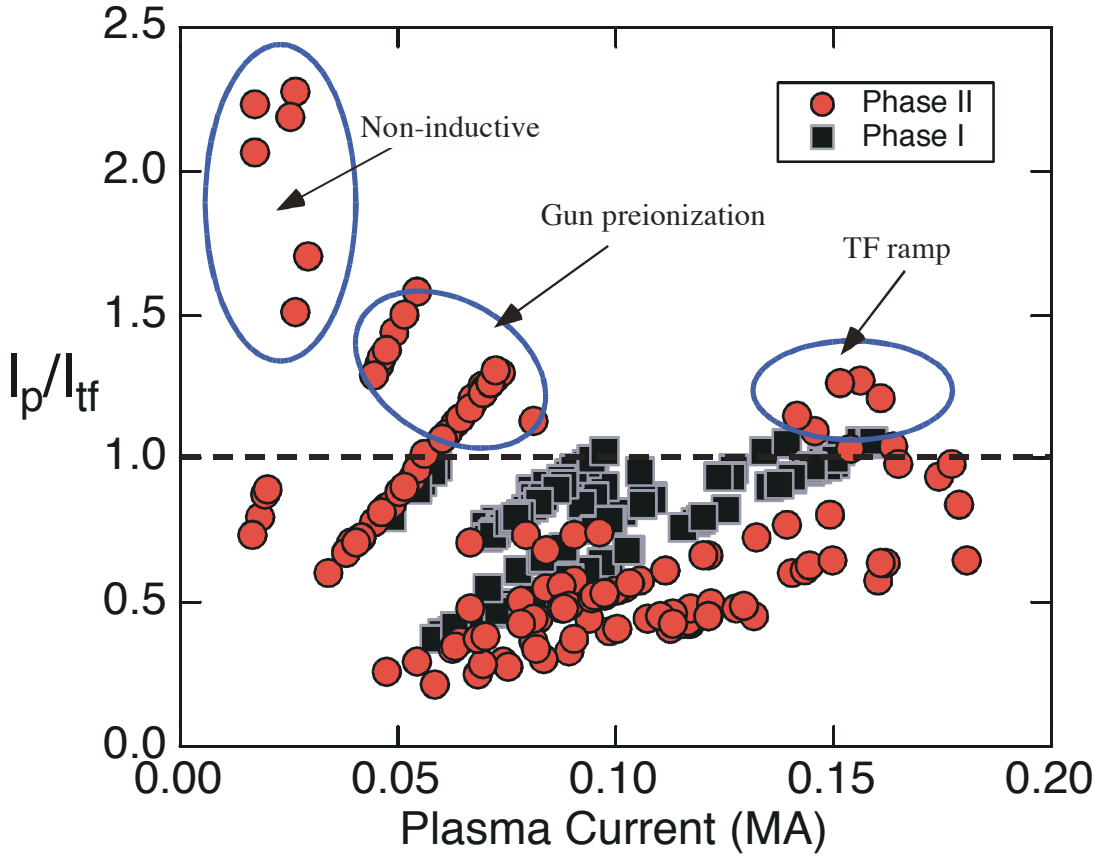
- **Fast TF rampdown, $\tau_{ramp} < \tau_{skin}$**
  - *Simultaneously high I_p & high I_p/I_{tf}*
  - *Allows access to high I_N, β_t plasmas*
  - *Adds edge current ⇒ develop hollow current profile during ramp*

- **Non-inductive startup with electrostatic current injection**
  - *Gives highest I_p/I_{tf} (~2.2)*
  - *MHD activity characteristically different from OH driven discharges*
  - *Adds J(r) relaxes from hollow profile ⇒ reverse shear early*

- **Ultra-low TF with guns as preionization source**
  - *Efficient OH driven discharges; $V_{loop} < 4$ V*
  - *MHD activity similar to high TF discharges*
  - *Expands operating space; Ultra-low TF = no ECH resonance for breakdown assist*

Separate experimental paths allow access to $I_p > I_{tf}$

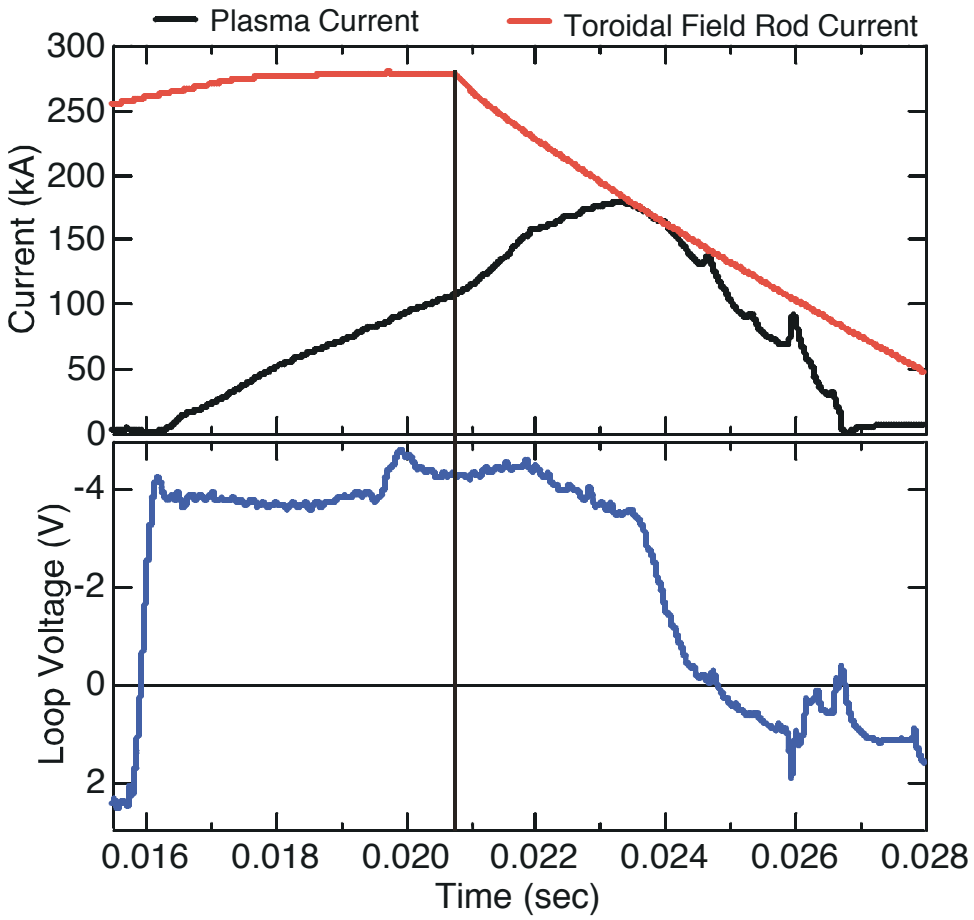
- **Current significantly above Phase-I $I_p \approx I_{tf}$ "soft-limit"**
- **New tools used to access new operating space**
  - *DC helicity injection ⇒ lowest I_p yet highest I_p/I_{tf}*
  - *Gun assisted startup ⇒ transient $I_p/I_{tf}>1$ w/ OH drive*
  - *TF ramps ⇒ highest I_p*
- **$I_p \leq I_{tf}$ is not an intrinsic limit**



Fast TF rampdown effective technique to increase I_p/I_{tf}

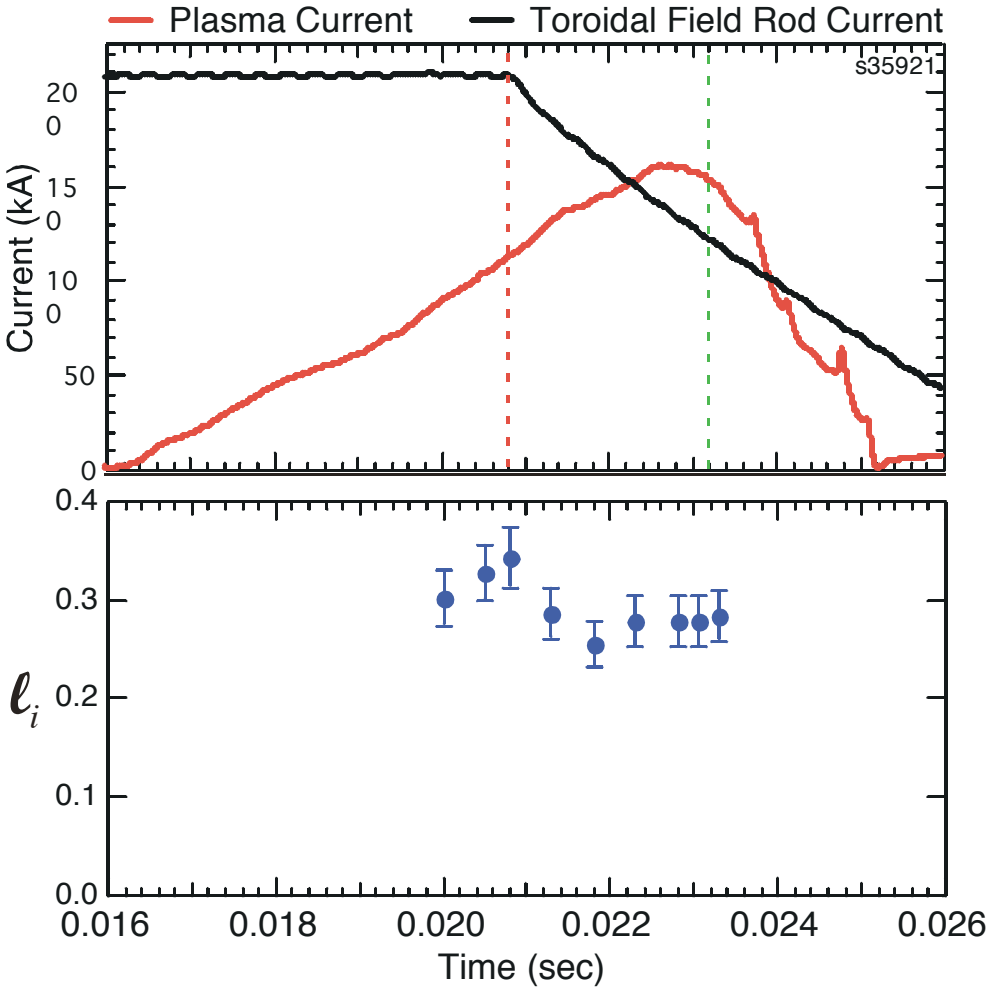
- **New TF coil set allows fast ramprates**
  - *Phase-I → 60 turn, high inductance set*
  - *Phase-II → 12 turn, $dI_{tf}/dt \sim 50$ MA/sec*
- **Current amplification seen during ramp**
  - *$dI_p/dt \sim 25$ MA/sec before ramp*
  - *$dI_p/dt \sim 35$ MA/sec after ramp*
  - *Attributable to non-zero poloidal resistivity*
- **Fast ramp occurs at end of typical discharge**
  - *Ramps begin after ~2 msec of high TF flattop*
  - *Allows high q in low resistance phase of discharge*

Example of TF rampdown

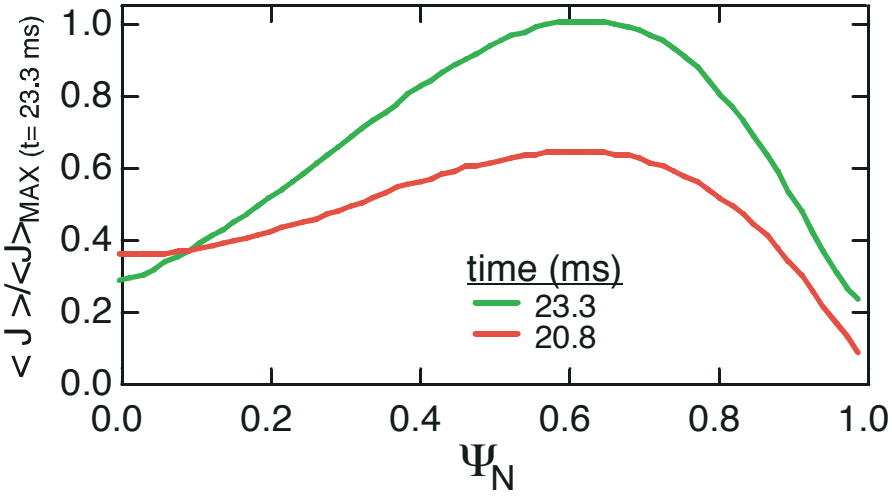


J(r) profile becomes more hollow during TF ramp

- **TF rampdown drives edge current**
  - *poloidal induction*
- **Edge current gives hollow J(r)**
  - ℓ_i *drops* ~ *20%*
- **q(r) modification affects mode activity**
- **Another tool for profile modification**

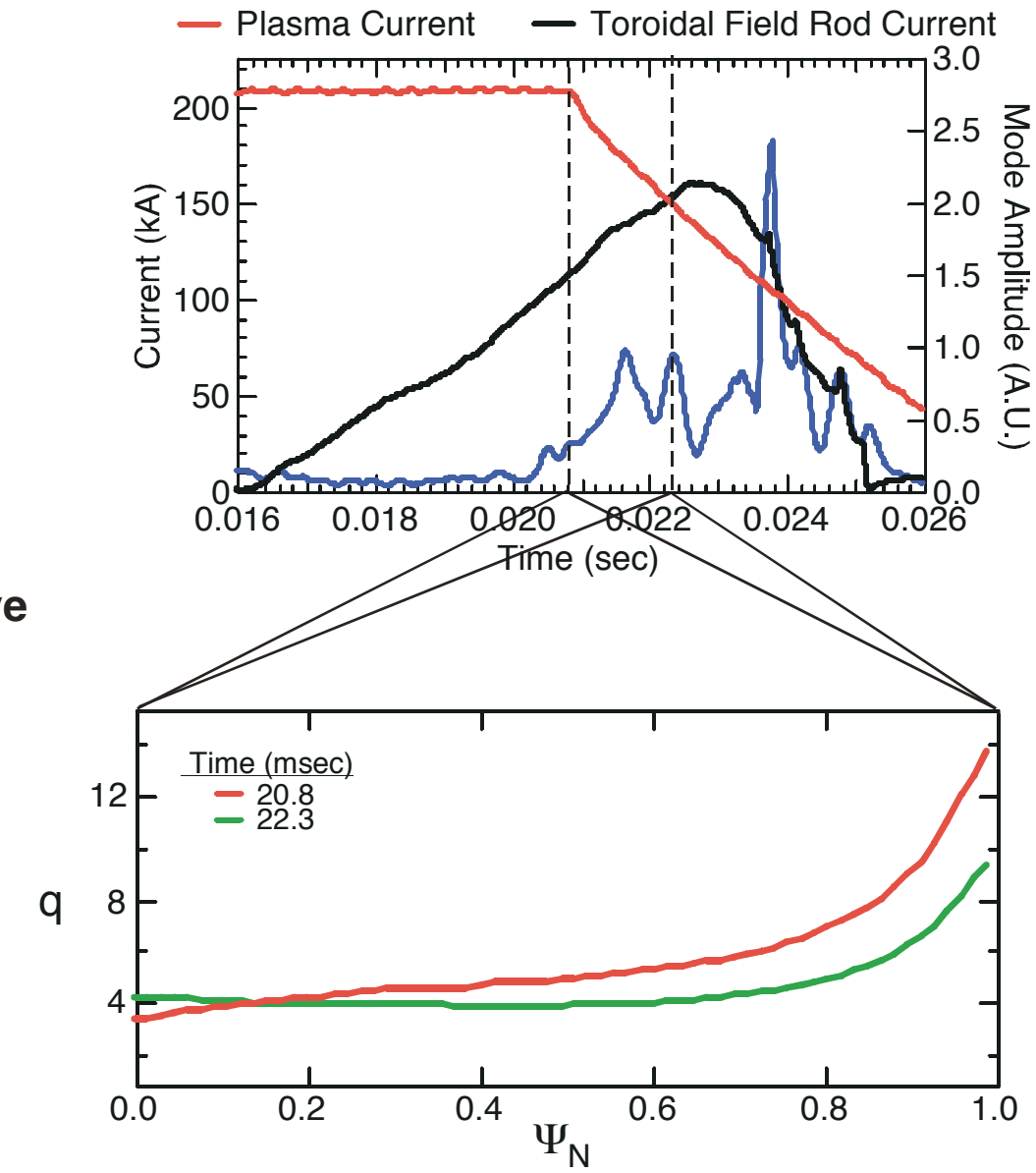


Current profile before and after TF ramp



Tearing mode activity increases as q profile flattens

- **Low level n=1 activity before ramp**
- **Instability grows during ramp**
- **q(r) modification via edge current drive possible mechanism**
  - *Equilibria suggest reduced dq/dr*



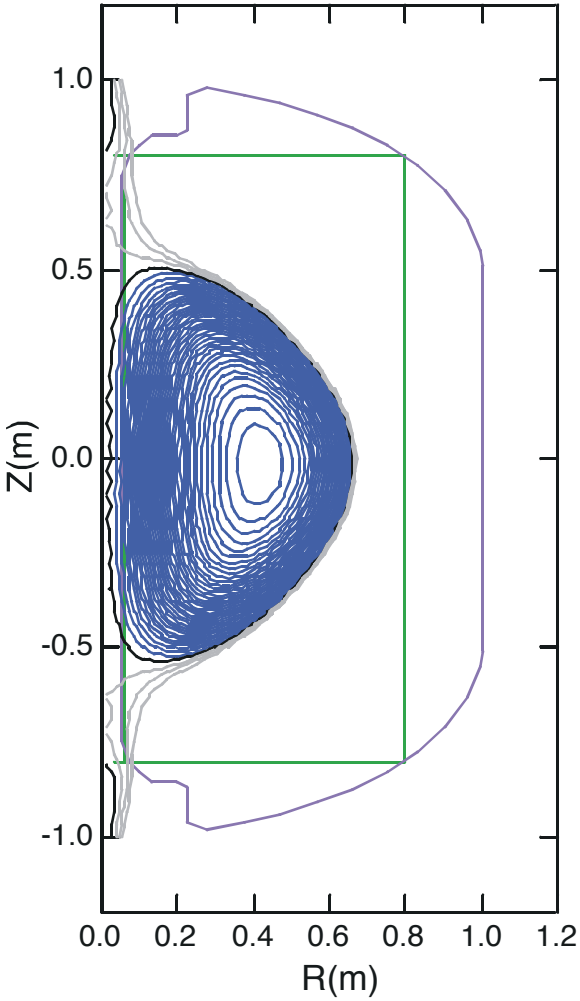
TF rampdown produces high l_N, β_t

- **Uses only magnetic sensors**
  - *Flux loops, Plasma Rogowski, pickup coils*
  - *No diamagnetic signal or T_e available for these discharges*
- **J(r) control different from Phase-I**
  - *TF ramp drives edge current*
  - *OH power only ~ 1/3 power*
  - *Much opportunity to expand/explore*
- **Experiments in high l_N, β_t to continue**
  - *Full V-sec & faster TF ramps*

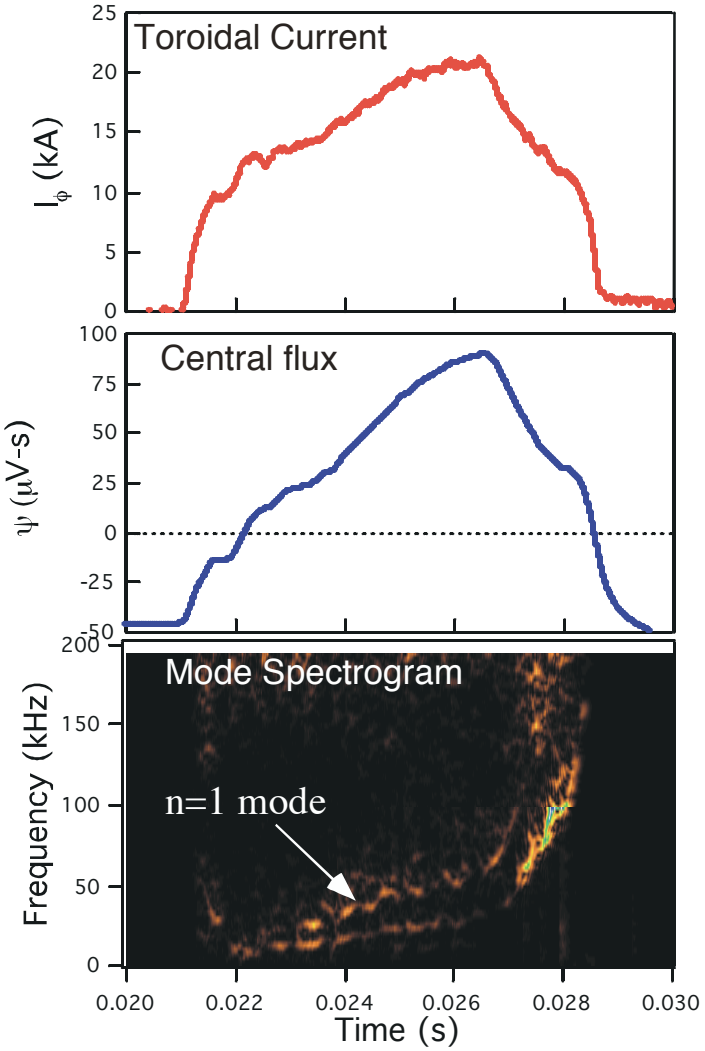
Reconstruction Parameter List

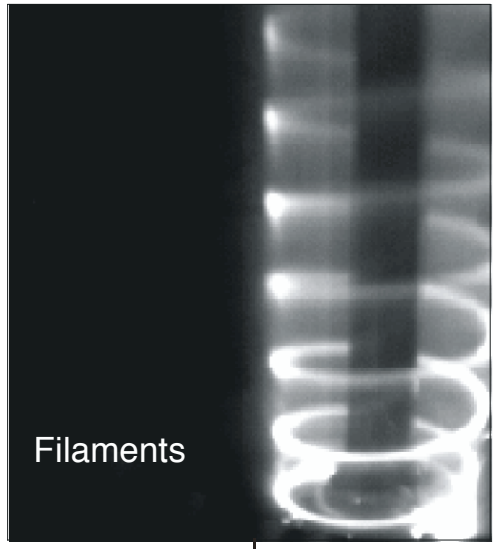
I_p (A)	161000
l_N	6.5
I_p/I_{tf}	1.23
ℓ_i	0.33
q_0	3.6
R_0 (m)	0.37
a (m)	0.32
A	1.17
β_t (%)	24
κ	2.2
q_{95}	4.8

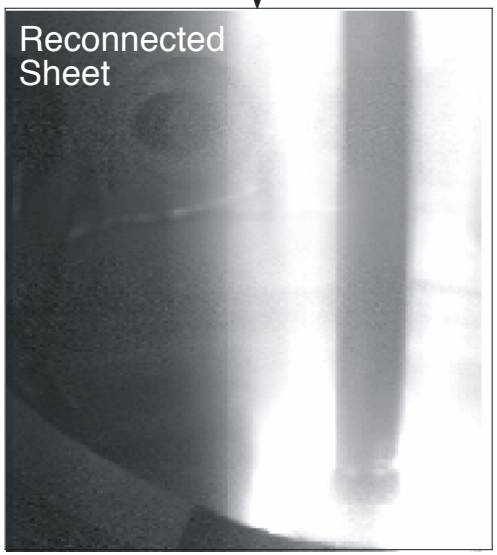
Reconstruction Flux Plot

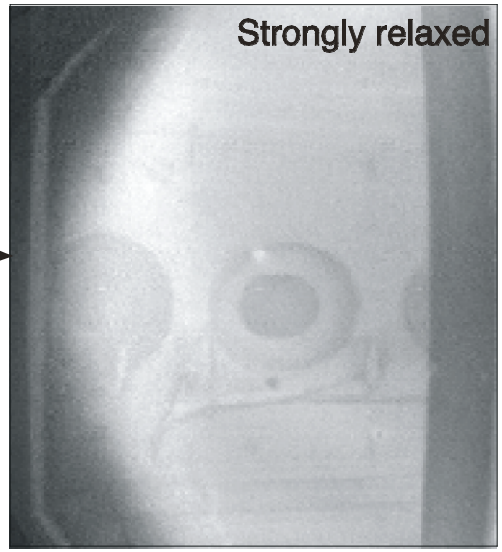


Plasma gun injectors noninductively produce high I_N plasmas





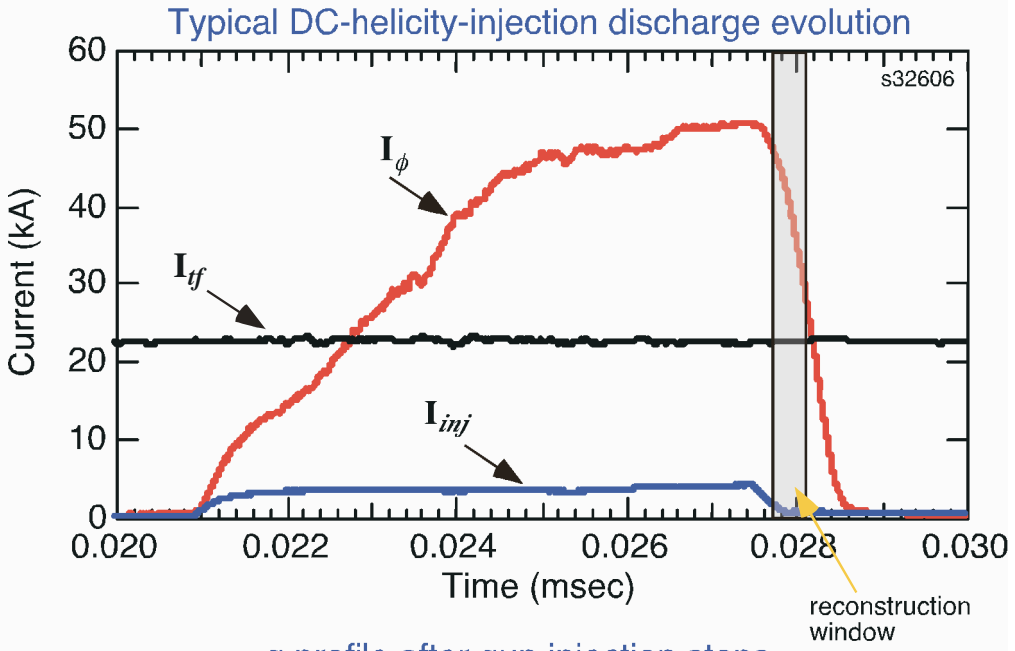


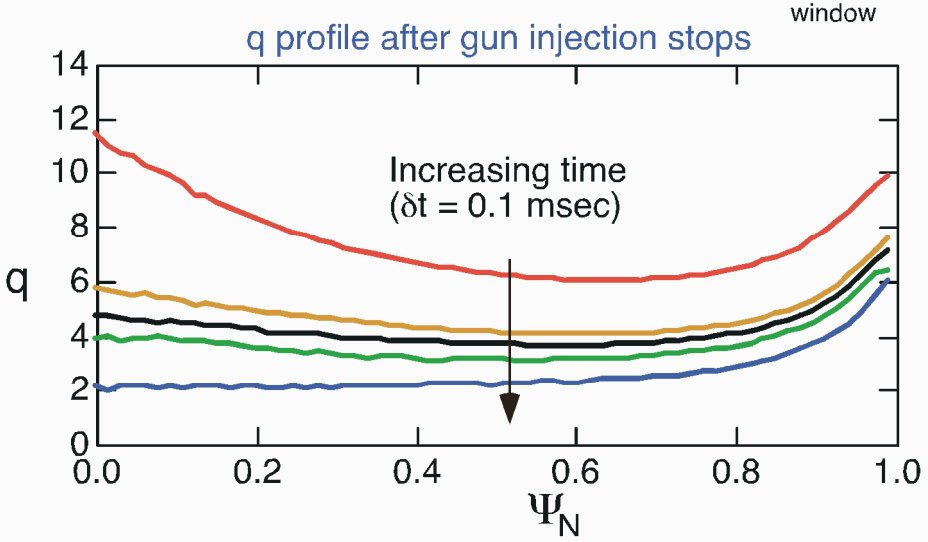


- $I_p > I_{tf}$ routinely observed
- Large-scale tearing modes not observed
  - some n=1 activity present
    - *likely line-tied kink, not tearing mode*

Edge current drive produces high I_N without low-order tearing modes

- Gun-produced plasmas readily achieve Ip > 2Itf
  - In agreement with helicity balance
  - Large-scale tearing modes not observed
- Equilibria suggest that current driven largely at edge
  - Hollow J(r) ⇒ reversed shear q
  - Low-order rationals do not appear
  - Region of low shear small
  - Not susceptible to virulent modes
- After gun shutoff, profile relaxes
  - I_p rampdown peaks current
  - Conventional ST q-profile observed late in discharge





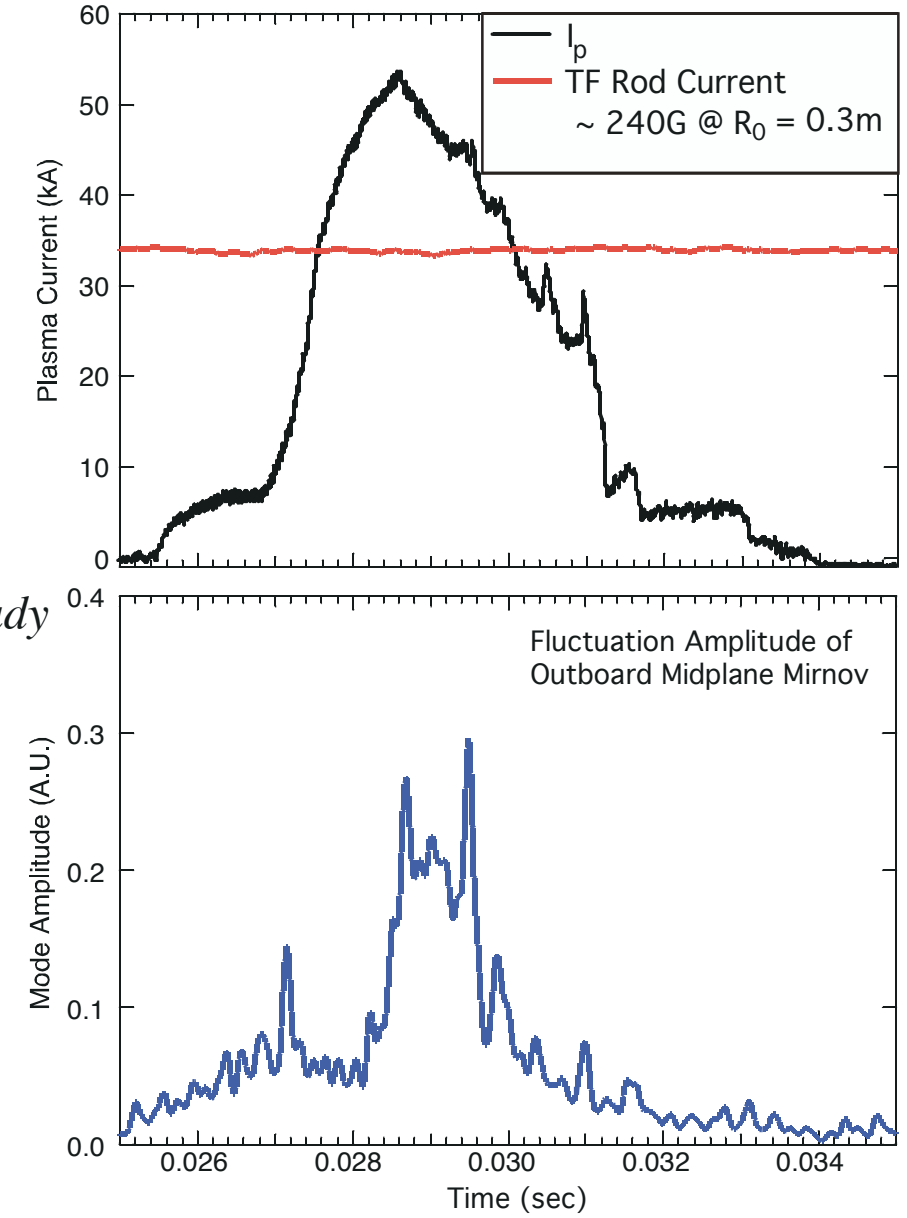
Guns provide preionization for ohmic operation at low B_t

- **Frees ohmic operations space from requirement of ECH resonance**
  - *Expands breakdown space*
    - *more PF control*
    - *better V-s utilization*

- **$I_p \sim 1.5 I_{tf}$ achieved to date**
  - *Transient discharges; limited by derated OH*
  - *Full OH; Increased V_{loop}, V-s $\Rightarrow$ further study*

- **Significance: No intrinsic limit in I_p/I_{tf}**

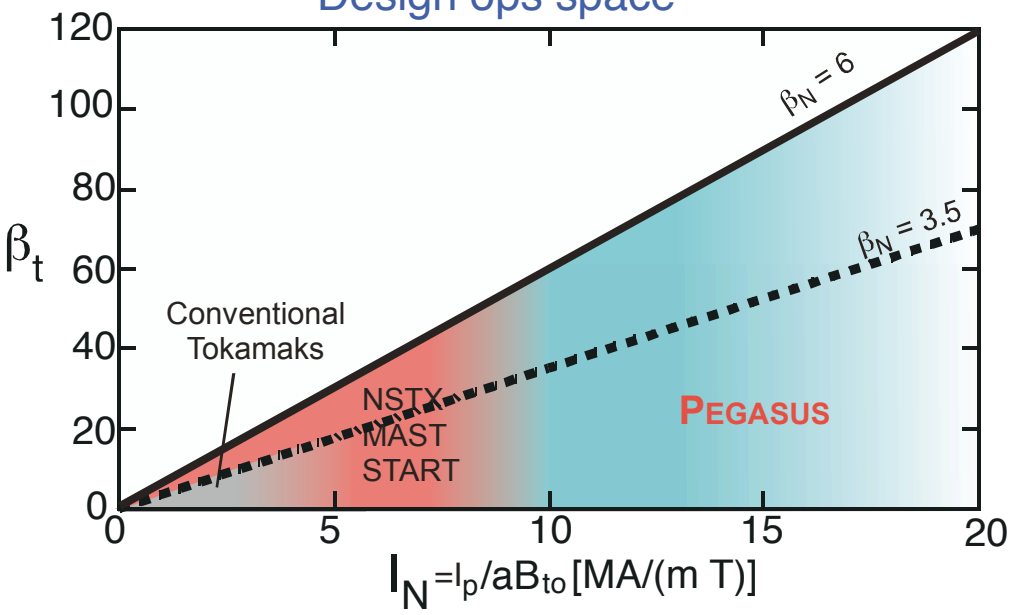
- **Further analysis in progress**
  - *Determine I_p/I_{tf} limiting mechanism*
  - *Characterize MHD @ $I_p > I_{tf}$*



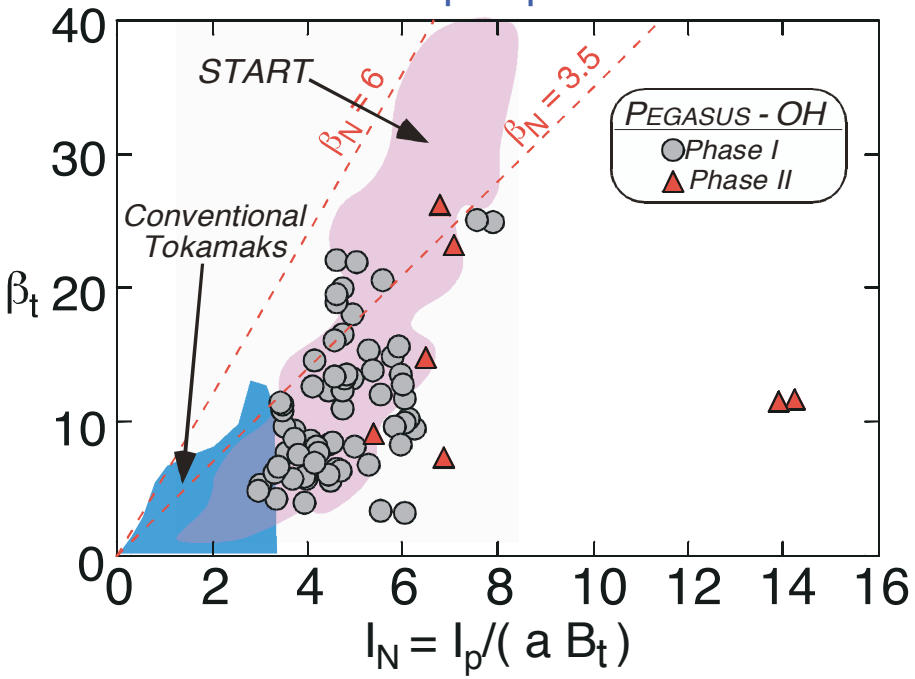
J(r) control techniques yield increased l_N

- **I_p/I_{tf} ~ 2.3 (l_N ~ 14) to date ⇒ Target: I_p/I_{tf} ~ 2-3 (l_N ~ 12-20)**
- **Continue with integration of 3 paths ⇒ should allow routine access**
- **Near term: Characterize kink stability limit**
- **Challenge β-stability limit w/ highest l_N & P_{aux} (HHFW &/or EBW)**

Design ops space

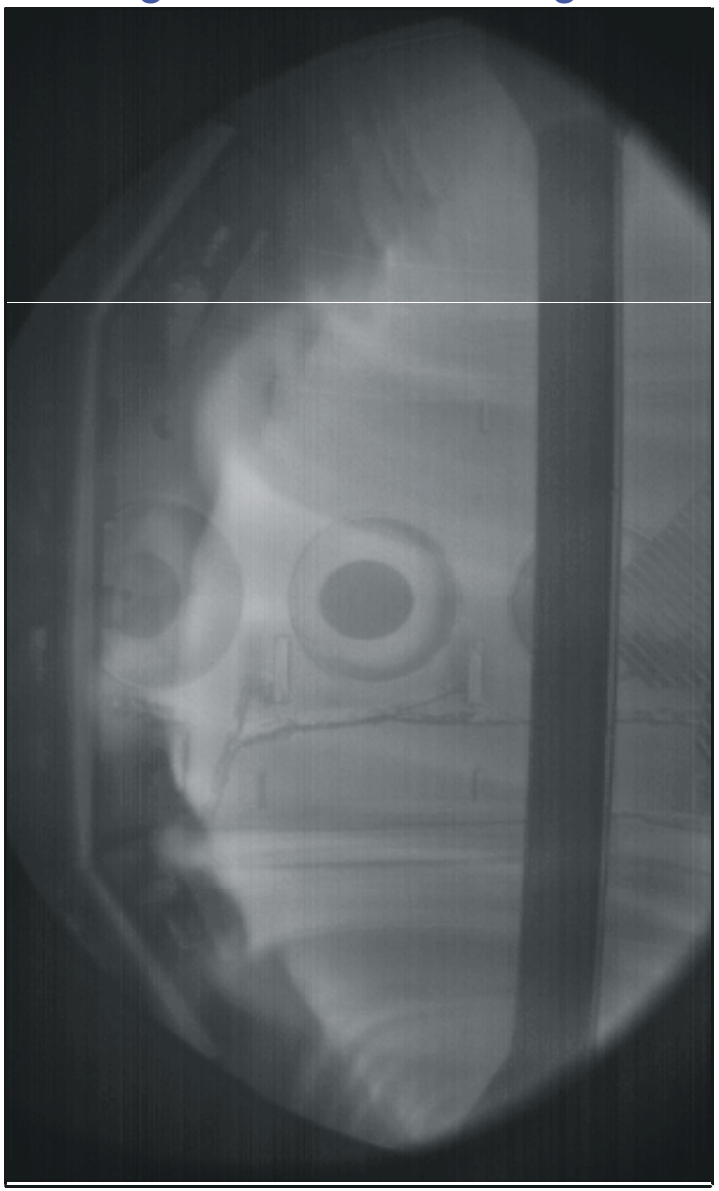


Realized ops space to date



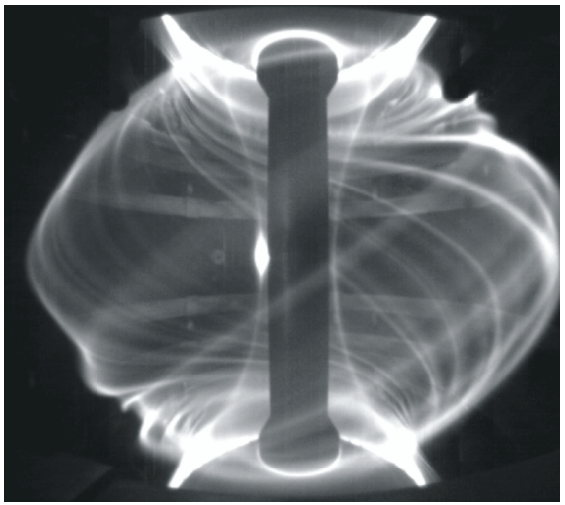
Edge instability observed in visible light

Edge Filaments on Pegasus



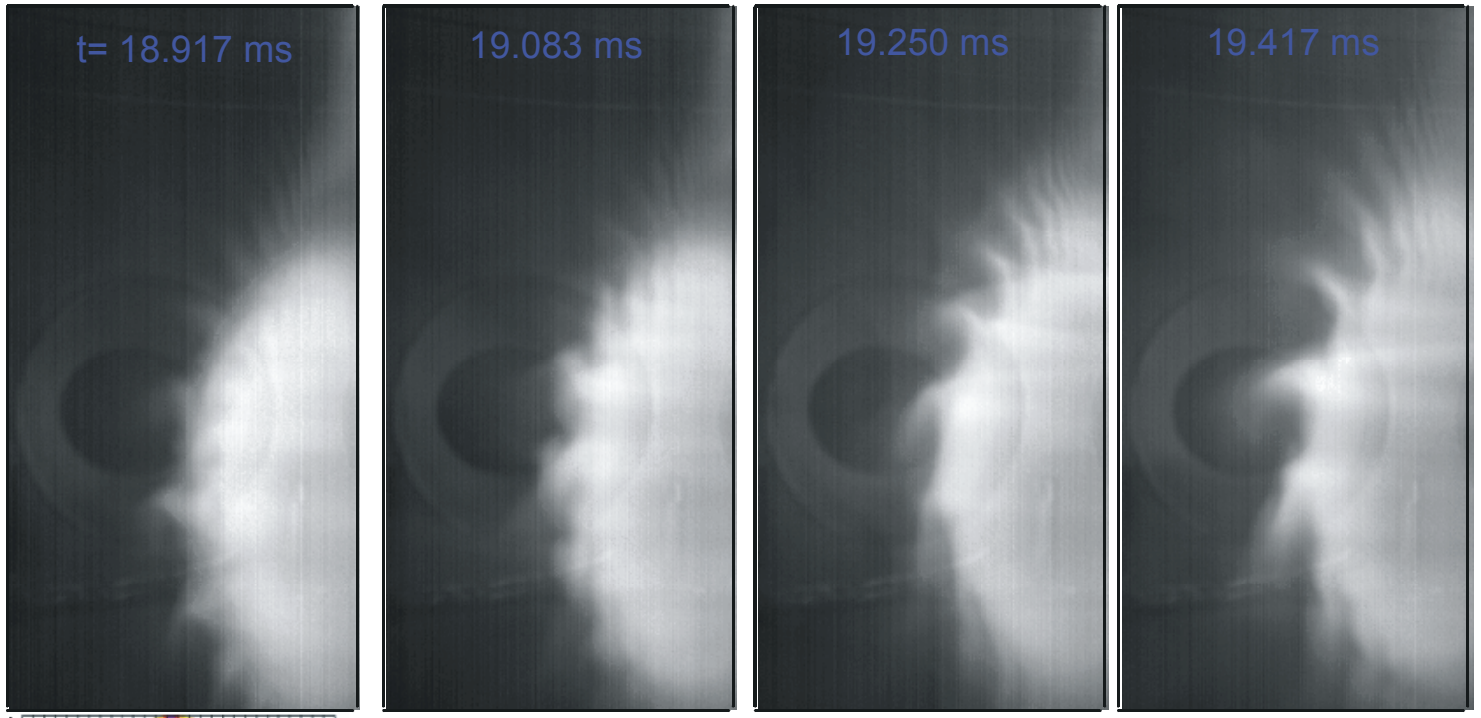
- Filamentary structures observed throughout discharge
  - Follow field lines
  - Appear to have moderate n (10-30)
  - Rotate in co-current direction
  - Sometimes appear to break away &propagate radially
- Visually similar to ELMs
  - Pegasus plasmas limited, likely L-mode

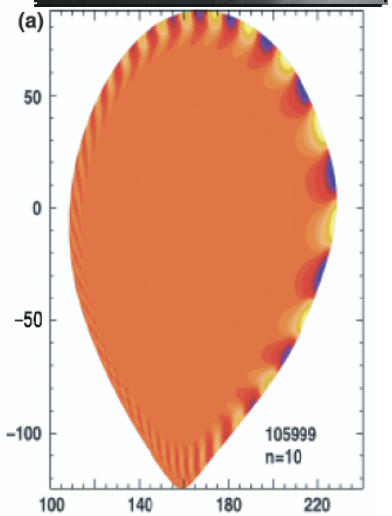
ELMs on MAST



B. Lloyd, 12th ST Workshop, Chengdu, 2006

Filaments appear early in discharge





- Structures first observed about 1 ms into discharge (I_p ~ 40 kA)
- Appear ballooning/interchange-like
  - Concentrated on low-field side
  - Lead to mixing of plasma and vacuum
  - Low pressure, high-J limit: peeling modes

ELITE calculation of density perturbations preceding ELM on DIII-D *(P. Snyder* et al., *PPCF* ***46*** *2004, A131)*

Resistive interchange calculation in DCON suggests peeling instability

- Resistive interchange:
  - $D_R < 0$ stable
  - Marginally stable at Pegasus edge

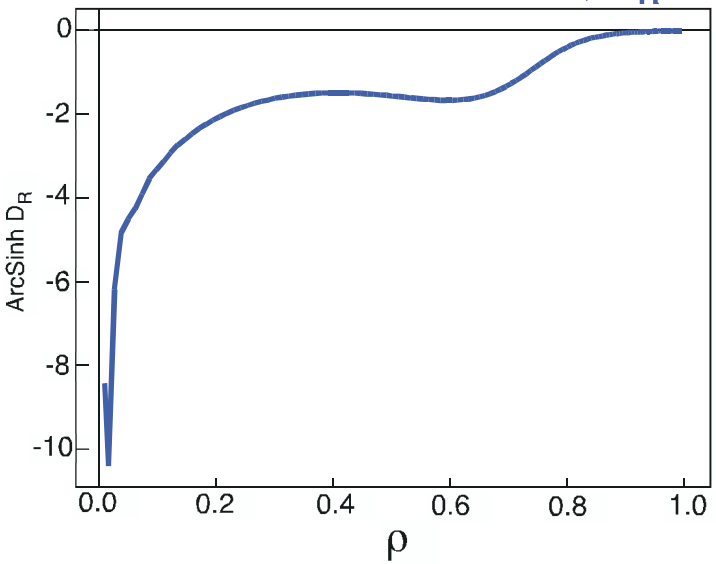
- Peeling mode:
  - For high A, low β ordering:

$$D_R < -\frac{qR}{s}\left(\frac{\overline{J_\parallel}}{B}\right)_{edge}$$

*Conner, Hastie et al., PoP **5** (1998)*

  - Less stable than resistive interchange
  - Unstable at edge?

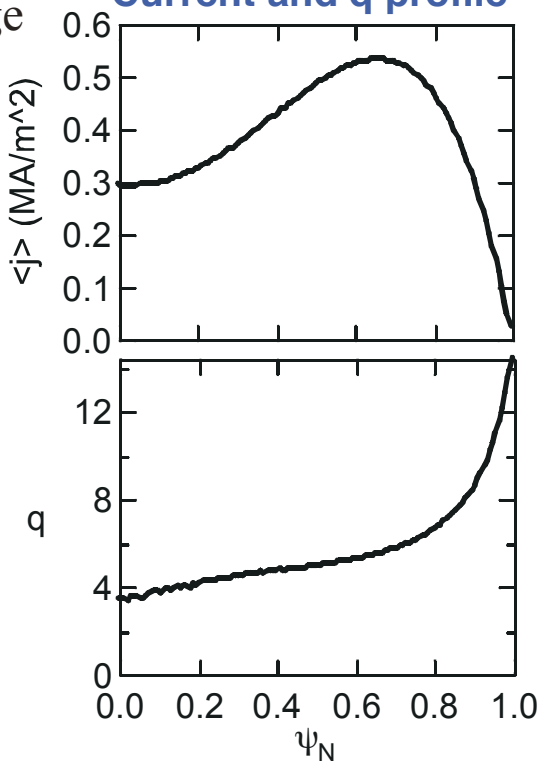
GGJ Resistive Criterion, D_R



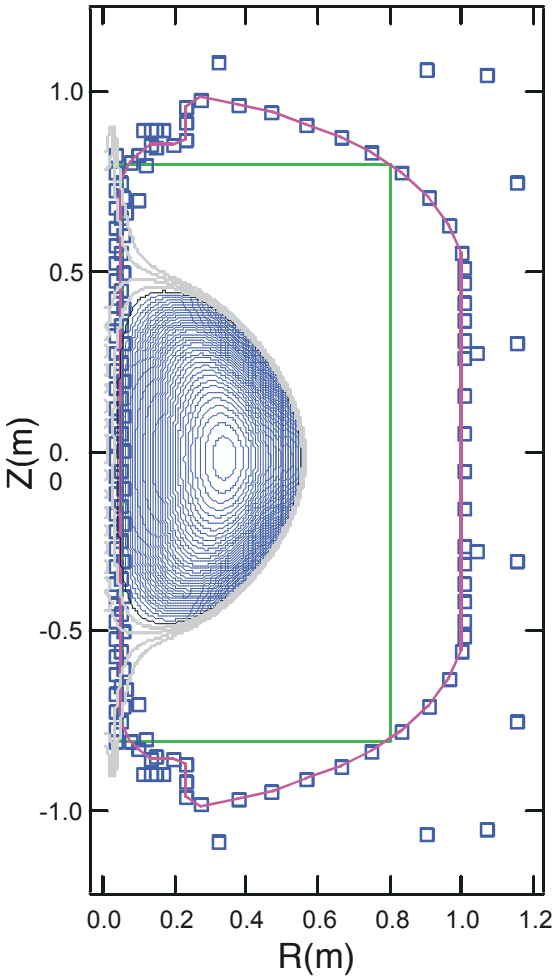
Parameter List

I_p (A)	164400
ℓ_i	0.32
q_0	3.4
R_0 (m)	0.30
a (m)	0.25
A	1.2
β_t (%)	2
κ	1.8
q_{99}	14

Current and q profile



Reconstruction Flux Plot



Pegasus Toroidal Experiment
University of Wisconsin-Madison

Summary

- In early experiments, MHD instabilities limited I_N ($I_p \sim I_{tf}$)
  - Large-scale low-order tearing modes
  - External kink mode

- Upgrades to experiment enable new J(r) manipulation techniques
  - Improved loop voltage control
  - High-current, low-inductance TF coil
  - Plasma gun helicity sources

- New techniques enable increased I_p/I_{tf}
  - Purely noninductive helicity injection
  - Plasma gun preionization at low B_t
  - Rapid B_t rampdown during discharge

- Edge instabilities recently observed
  - Located mostly on low-field-side, moderate n, aligned with **B**
  - Possibly peeling modes